Journal of Experimental Psychology: General

© 2021 American Psychological Association
ISSN: 0096-3445

2022, Vol. 151, No. 5, 1018–1034
https://doi.org/10.1037/xge0001116

Guidance of Attention From Visual Working Memory Is Feature-Based, Not Object-Based: Implications for Models of Feature Binding

Daniel D. Thayer[1], Brett Bahle[2], and Andrew Hollingworth[3]
[1] Department of Psychological and Brain Sciences, University of California, Santa Barbara
[2] Department of Psychology and The Center for Mind and Brain, University of California, Davis
[3] Department of Psychological and Brain Sciences, The University of Iowa

A classic question in visual working memory (VWM) research is whether features from the same object are bound directly in an integrated representation or are maintained separately and bound only indirectly though shared location. Here, we examined this question using a novel method that probed the *effects* of VWM on the guidance of attention (rather than requiring explicit access to VWM content, as has typically been used). Participants remembered two color-shape conjunction objects. During a retention-interval search task, they searched for a target letter among distractor letters superimposed over color-shape conjunction items. There were two critical conditions. In the *same-object-match* condition, one search item matched both the color and shape of a single remembered object. In the *different-object-match* condition, one search item matched the color from one remembered object and the shape from the other. Robust effects of VWM-based guidance were observed, both when probing the incidental guidance of attention (Experiments 1 and 2) and the strategic guidance of attention (Experiment 3). Critically, in none of the experiments was the magnitude of guidance greater for same-object-match than for different-object-match. The results indicate that the representational units of guidance from VWM are individual features rather than integrated objects.

Keywords: visual working memory, visual search, attentional guidance

We perceive and remember the visual world in terms of discrete visual objects that are composed of values on different feature dimensions. One of the core debates in the field of visual working memory (VWM) is how those features are bound together. Feature values from the same perceptual object may be directly bound to each other within an integrated VWM representation (Luck & Vogel, 1997; Vogel et al., 2001). Alternatively, feature values from a perceptual object may be maintained separately (Bays et al., 2011; Fougnie & Alvarez, 2011; Fougnie et al., 2013; Wheeler & Treisman, 2002) and bound only indirectly by virtue of being associated with the same spatial location (Kahneman et al., 1992; Schneegans & Bays, 2017).

Empirically, there are three senses in which VWM operations exhibit object structure. First, feature memory performance is improved when features are presented within a smaller number of objects rather than distributed across a larger number of objects (Fougnie et al., 2013; Olson & Jiang, 2002; Vogel et al., 2001; Wheeler & Treisman, 2002; Xu, 2002a, 2002b). Second, when encoding a task-relevant feature of an object, irrelevant features are also encoded and can influence performance; the perceptual object appears to be the primary unit of encoding (Foerster & Schneider, 2018; Gao et al., 2011; Hollingworth & Bahle, 2020b; Hollingworth & Luck, 2009; Hollingworth & Matsukura, 2019; Hollingworth et al., 2013a, 2013b; Hyun et al., 2009; Marshall & Bays, 2013; Matsukura & Vecera, 2011; Shen et al., 2013; Wheeler & Treisman, 2002; Yin et al., 2012; but see Serences et al., 2009; Woodman & Vogel, 2008). Finally, operations involving access to VWM representation and their comparison with perceptual input are often influenced by object location (Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Jiang et al., 2000; Kahneman et al., 1992).

These three phenomena are potentially consistent with an integrated-features, direct-binding model of VWM structure (Luck & Vogel, 1997; Vogel et al., 2001). However, they can also be explained under a separate-features, indirect-binding model (Kahneman et al., 1992; Schneegans & Bays, 2017). Specifically, the phenomenon of improved memory performance when features are associated with a smaller number of objects can be explained by limitations on the number of feature-location bindings that can be encoded/maintained (Wang et al., 2016). The phenomenon of object-based encoding (that both relevant and irrelevant features are encoded into VWM) can be explained by a close relationship between perceptual attention and memory encoding (e.g., Schmidt et al., 2002), with attentional selection occurring primarily on the basis of location and object. Finally, object-based effects in access to VWM representations can be explained by the utility of remembered location as cue for the retrieval of associated properties (Hollingworth & Rasmussen, 2010; Kahneman et al., 1992).

To distinguish between integrated- versus separate-feature models of VWM structure, researchers have probed for correlations between the report of different features from the same perceptual object. If features are bound directly to each other in VWM, with

---

This article was published Online First November 4, 2021.

Daniel D. Thayer https://orcid.org/0000-0002-0053-4243
Andrew Hollingworth https://orcid.org/0000-0002-7613-6786
Correspondence concerning this article should be addressed to Andrew Hollingworth, Department of Psychological and Brain Sciences, University of Iowa, G60 Psychological and Brain Sciences Building, Iowa City, IA 52242, United States. Email: andrew-hollingworth@uiowa.edu

forgetting occurring at the level of integrated object representations, then there should be a robust relationship of this type: features should tend to be remembered or forgotten together. In contrast, if feature values are maintained separately, then their representational fates may be largely independent. Several studies have found only weak correlations between the report of different feature values associated with the same remembered object (Bays et al., 2011; Fougnie & Alvarez, 2011; Fougnie et al., 2013). Although such weak correlations do not support direct binding models, they also fall short of providing unambiguous evidence for feature independence. However, a possible source of within-object correlations in these tasks is that they required explicit access to and report of remembered features. In the course of explicit report, participants are likely to have used location as a retrieval cue (Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Jiang et al., 2000; Kahneman et al., 1992), whether cued by location or by a nonspatial feature (Schneegans & Bays, 2017). The binding of feature values to a shared location could have introduced retrieval contingencies that led to feature report correlations in the absence of any direct feature-to-feature binding.

In the present study, we developed a novel approach to test this basic representational issue. Instead of requiring explicit report of the content of VWM, we probed the *effects* of VWM on other, ongoing cognitive operations. We exploited the fact that there is a close functional relationship between VWM and attention: VWM maintains feature templates that bias attention toward locations containing matching stimuli during visual search (Bundesen, 1990; Bundesen et al., 2005; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Hamker, 2005), and this occurs even when the content of VWM is either irrelevant to or in conflict with the current task set, suggesting that guidance is, to some extent, an automatic process (Olivers, 2009; Olivers et al., 2006; Soto, Heinke, et al., 2005; Soto & Humphreys, 2009). If VWM automatically influences the allocation of attention, then we can ask whether this guidance is more consistent with the predictions of a direct-integration model or with those of a separate-features model. That is, if features from an object are directly integrated in VWM, their effects on the guidance of attention should be strongly linked (i.e., strong object-based guidance). If, however, features from an object are maintained independently and bound only indirectly through shared location, then their effects on the guidance of attention may be independent (i.e., feature-based guidance). The broad approach does not require explicit access to remembered items in VWM during the portion of the trial when binding is probed (attention guidance during visual search). By eliminating the demand for retrieval, which is likely to be mediated by location, the present study potentially provides a more direct test of the core theoretical question of directly integrated versus separate feature representations.

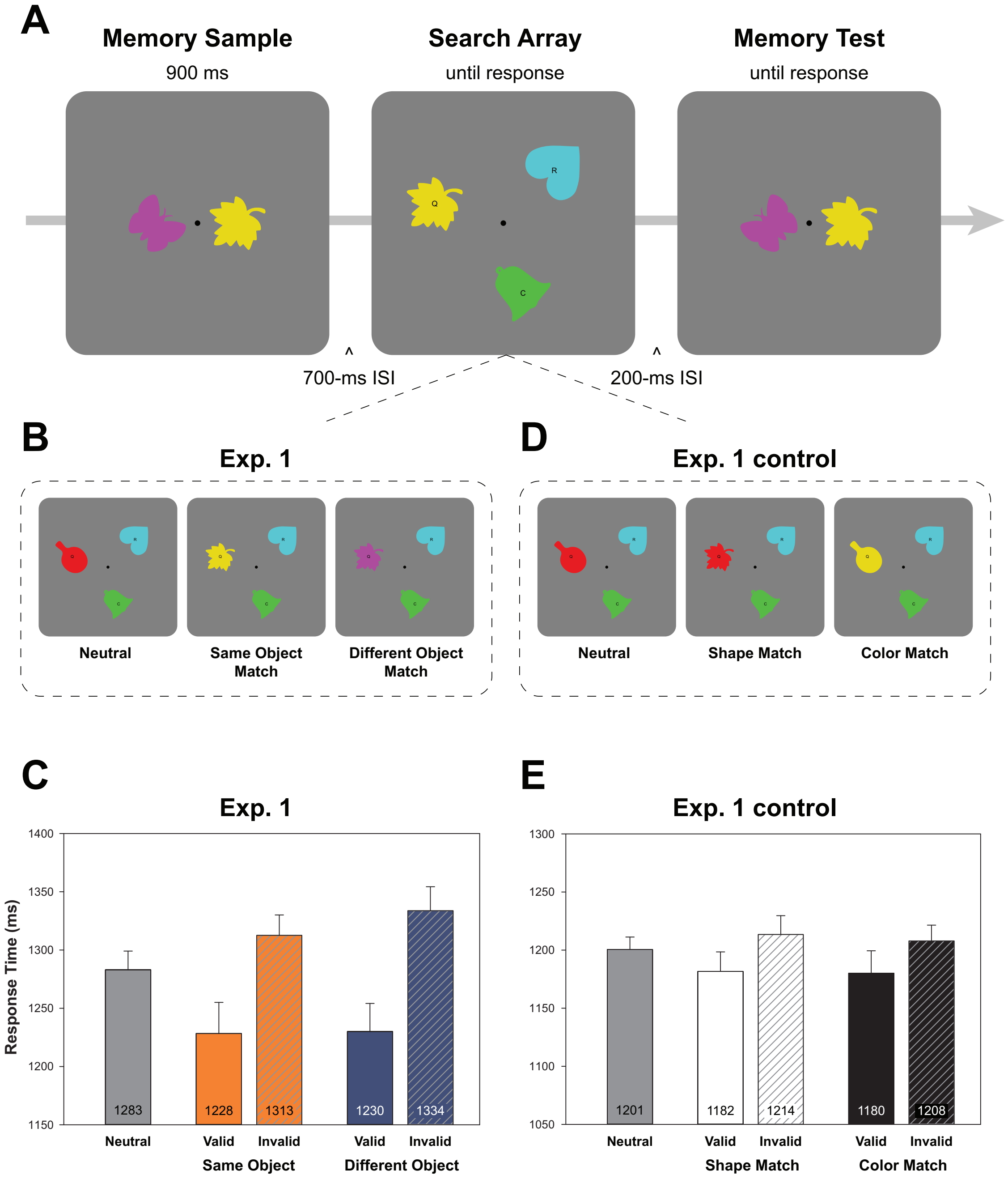
Surprisingly, no published studies have tested whether the interaction between VWM and spatial attention is influenced by object structure. Several have demonstrated that task-irrelevant features of objects, encoded automatically in to VWM, guide attention and gaze (Foerster & Schneider, 2018; Hollingworth & Bahle, 2020b; Hollingworth & Luck, 2009; Hollingworth & Matsukura, 2019; Hollingworth et al., 2013a, 2013b). In these studies, participants remembered objects composed of a feature value on a relevant (tested) dimension and a value on an irrelevant dimension. Stimuli matching the value on the irrelevant dimension reliably recruited attention and gaze, even when matching values were associated only with distractors. This work provides clear evidence of object-based encoding into VWM (that both task-relevant and irrelevant features are encoded, reviewed above), and it suggests that, once encoded, task-irrelevant features can influence spatial attention. However, the data fall short of demonstrating that the guidance process itself—the mechanisms by which VWM representations influence attentional priority—is object-based. That is, once encoded, task-irrelevant features could have influenced attentional priority in a manner that was independent of object structure.

To probe object-based guidance, one would need to test whether perceptual stimuli that exactly match an object in VWM receive preferential priority relative to matching stimuli that do not but are otherwise equated for feature overlap (e.g., an equivalent match to the same number of features but distributed across separate object representations in VWM). Recently, Bahle et al. (2020) implemented an initial test of this sort while probing a different theoretical issue, the capacity of guidance from VWM. Using a redundancy gains paradigm, they examined simultaneous guidance from multiple features in VWM. Participants were cued to search for the presence of either of two features on a given trial, such as a color and a shape. On target-present trials, the target matched one of the features (single-target) or both (redundant-target). In the latter condition, guidance from the two features was found to violate the race model inequality (Miller, 1982), suggesting the two feature values coactivated (or summed) on the priority map used to guide attention. Critically, evidence of coactivation was observed both in an experiment when the two cued features were remembered as part of a single object in VWM and in an experiment when they were associated with different objects. These results are suggestive, as they demonstrate that an object match is not a necessary condition for coactive, VWM-based guidance. However, the redundancy gains method used in Bahle et al. can only probe for the presence of coactivation; it provides no means to compare the magnitude of coactivation across experiments or conditions. Thus, the Bahle et al. data cannot address the present question of whether guidance from VWM is object-based: i.e., more robust when feature matches are associated with the same object versus different objects in VWM.

To test this question directly, in the present study we translated the logic of Duncan (1984) to the domain of VWM-based attention guidance. In Duncan's study, participants were more accurate in reporting two features when they appeared as part of the same perceptual object versus when they were split across two overlapping perceptual objects, indicating that selection was sensitive to object structure and was not purely space-based. We applied this logic by comparing attentional guidance generated by a perceptual match to two features from the same object in VWM versus two features from different objects. In Experiments 1 and 2, participants performed a visual search task during the retention interval of a VWM task (Figure 1A). The memory task required participants to either remember the orientations of two color-shape conjunction objects (Experiment 1) or to remember the specific binding of color and shape for each object (Experiment 2). For the search task, participants searched through three color-shape conjunction objects to find the one object with a superimposed target letter ('Q' or 'P') among objects with distractor letters ('C' and 'R'). In the *neutral* condition, none of the search objects matched the shape or color of a remembered object. In the *same-object-match* condition, one search object matched both the shape and color from one of the remembered items. In the *different-object-match* condition, one search object matched the shape from one of the remembered items and the color from the other remembered item. Note that these latter two conditions were equated for the number of matching features. In addition, in each of the two match conditions, the target letter either appeared on the

Figure 1

Experiment 1 Design and Results



Note. (A) Sequence of events in a trial of Experiment 1. Participants remembered the orientations of two colored shapes for a memory test at the end of the trial. During the retention interval, they searched among a set of colored shapes for a target letter (‘Q’ or ‘P’) among distractor letters (‘C’ and ‘R’). (B) In the neutral condition, none of the three search objects matched the remembered colors or shapes. In the same-object-match condition, one of the search objects was an exact match to both the color and the shape of one of the two memory objects. In the different-object-match condition, one of the search objects matched the color from one of the memory objects and the shape from the other memory object. In the two match conditions, the target letter either appeared on the matching object (valid condition) or on one of the two mismatching objects (invalid condition). The magnitude of the validity effect provides an index of guidance by visual working memory. (C) Mean response time (RT) in Experiment 1 as a function of match condition and validity. (D) To ensure that both color and shape guide attention in this paradigm, in a control experiment, matches to memory in the search display were only on a single dimension. Specifically, in the shape-match condition, one search object matched the shape of one of the two memory items (but neither of the colors). In the color-match condition, one of the search objects matched the color of one the two memory items (but neither of the shapes). (E) Mean RT in the Experiment 1 control as a function of match condition and validity. In Panels C and E, the values represented by the bars are inset at the base of each bar. Error bars are condition-specific, within-subject 95% confidence intervals (Morey, 2008). See the online article for the color version of this figure.

matching object (*valid*) or on one of the two mismatching objects (*invalid*). VWM did not predict target location, and these experiments therefore probed the incidental guidance of attention from VWM.

In this method, the magnitude of the expected validity effect on response time (RT) provides an index of the strength VWM-based guidance (Hollingworth & Bahle, 2020b). If the guidance of attention from VWM is strongly object-based, with guidance based on a match to directly integrated feature representations, we should observe a larger validity effect in the same-object-match condition than in the different-object-match condition. If, instead, the guidance of attention from VWM is purely feature-based, applied independently for each matching feature, then the combined effects of the individual feature matches should be equal to the attentional priority derived from an object match, leading to minimal or no difference between the two conditions.

In Experiment 3, the paradigm was modified to test the *strategic* guidance of attention from VWM by either eliminating invalid trials so that the remembered items predicted the search target (Experiment 3A) or by requiring participants to use the remembered object properties to locate the search target and identify the superimposed letter on that object (Experiment 3B). The two critical conditions (same-object match and different-object match) were again included, with the same prediction as developed above.

In all experiments, we observed robust attentional guidance by the content of VWM. Control conditions ensured that both color and shape guided attention simultaneously in each version of the paradigm. Critically, there was no difference in guidance between the same- and different-object-match conditions. That is, the guidance of attention from VWM was not strongly object-based. The results are consistent with the view that (a) features from the same object are maintained independently in VWM and bound only indirectly, and (b) features encoded from the same object have independent effects on the guidance of attention.

Experiment 1

In Experiment 1, we implemented the basic method illustrated in Figure 1A. For the memory task, participants remembered the orientations of two shape-color conjunction objects. We could be confident that participants would also encode the shapes and colors of the memory stimuli and that these values would guide attention (Foerster & Schneider, 2018; Hollingworth & Bahle, 2020b; Hollingworth & Luck, 2009; Hollingworth & Matsukura, 2019; Hollingworth et al., 2013a, 2013b). The critical data came from validity effects during the search task as a function of same- versus-different object match. The remembered features were unpredictive of the target location in the search task, probing the incidental guidance attention from the content of VWM.

Method

Participants

Participants (18–30 years old) were recruited from the University of Iowa undergraduate subject pool and participated for course credit. All human subjects' procedures were approved by the University of Iowa Institutional Review Board. Given that the research question here is novel, and there is no existing effect in the literature upon which to base a power estimate, an *N* of at least 40 was chosen to ensure sufficient power to detect a medium-sized effect in the comparison of the validity effects across same- and different-object match conditions. Specifically, a sample of 40 has 80% power to detect an effect of $\eta_p^2 = .18$ (calculated using Gpower).

Due to novel coronavirus restrictions, the participants completed the experiment online using their own computers, rather than in the laboratory. We expected significant variability in performance and set relatively stringent inclusion criteria. Participants were excluded if less than 80% of their trials would have been used in the RT analysis (based on search accuracy and outlier trimming, specified below). Participants were also excluded if they performed below 65% correct on the memory task, as reliable maintenance of the stimuli in memory was a necessary condition for observing attention guidance. Participation "slots" were posted online, and the number of participants meeting inclusion criteria was monitored. Given that multiple participants often completed the experiment simultaneously, we could not control the exact number of participants meeting criteria. Sixty-six participants completed the experiment, with 44 meeting inclusion criteria. Of these 44, 29 were female, 13 were male, and two did not report gender.

Stimuli and Procedure

Because the monitors and viewing distances varied across participants, we report stimulus size in absolute pixel values and colors in RGB coordinates. The stimulus displays were 1024 × 768 pixels. All stimuli were presented against a gray (128, 128, 128) background with a central black dot (16-pixel diameter). The memory and search objects were each a conjunction of color and shape. We chose five highly discriminable colors and five highly discriminable shapes to minimize effects of display monitor variability. The five colors were yellow (230, 219, 38), red (225, 20, 36), green (44, 234, 25), fuchsia (224, 0, 233), and cyan (62, 230, 229). The five shapes were leaf, bell, paddle, heart, and butterfly. Each of the stimuli could appear in one of four orientations, with the principal axis of the object at 45°, 135°, 225°, or 315°.

In the memory sample display, two colored shapes (each 150 × 150 pixels) were centered 110 pixels to the left and right of screen center. On each trial, the color and shape values were chosen randomly without replacement from the five alternatives on each dimension. The orientation of each memory sample object was also selected randomly from the four possible orientations. In the memory test at the end of the trial, the two memory objects either retained their original orientations (*same* response), or one of the objects changed to a different orientation selected randomly from the remaining three (*changed* response). Note that the orientation memory test did not explicitly require memory for color or shape. We expected that there would be minimal guidance of attention from remembered orientation itself (Hulleman, 2020). However, we could be confident that color and shape would nevertheless be encoded into memory and would guide attention (Foerster & Schneider, 2018; Hollingworth & Bahle, 2020b; Hollingworth & Luck, 2009; Hollingworth & Matsukura, 2019; Hollingworth et al., 2013a, 2013b). This design largely eliminated the possibility that participants would strategically attend to matching search stimuli to improve performance on the memory test. We also sought to ensure that guidance during search was not governed solely by color, as color generates particularly robust attentional guidance (Alexander et al., 2019; Hulleman, 2020; Williams, 1967; Zelinsky, 1996). Orientation information was carried by shape, so we expected participants to attend more to shape than to color during encoding, potentially equating guidance by the two feature dimensions. This was confirmed in a control experiment, reported subsequently. Finally, to ensure that participants did not strategically attend to matching shapes in the search display to refresh their memory for orientation, on half of the trials with a shape match, the orientation of the shape in the search display was changed (to the orientation that would become the changed orientation in the test display). Thus, the orientation of a matching shape in the search display did not predict the correct response on the memory test (for similar methods, see Bahle et al., 2018; Hollingworth & Beck, 2016; Olivers et al., 2006).

For the search task, the search array consisted of three object items (each 150 × 150 pixels) distributed evenly on a virtual circle around central fixation with a radius of 200 pixels. The position of the first item was selected randomly from a value of 1° to 360° around the virtual circle. The two remaining items were offset from this location by 120° and 240°. This varied the absolute locations of the objects on a trial-by-trial basis, reducing the possibility that participants would develop a scripted spatial sequence during search. As illustrated in Figure 1B, in the *neutral* condition, the three search objects were randomly constructed from the three colors and the three shapes not used in the memory sample display. Thus, there were no matches to the remembered feature values. In the *same-object-match* condition, one of the search objects was an exact match to both the color and shape of one of the two memory objects (randomly selected). In the *different-object-match* condition, one of the search objects matched the color from one of the memory objects and the shape from the other memory object (matching features randomly selected). Thus, the two match conditions were equated for the number of feature matches. (As described above, when there was a shape match, on half the trials the matching search item retained the original, remembered orientation, and on half the orientation was changed.) The logic of the object-match manipulation assumes that attention is guided by VWM even when multiple objects are maintained in VWM, which has broad empirical support (Bahle et al., 2018; Bahle & Hollingworth, 2019; Bahle et al., 2020; Beck & Hollingworth, 2017; Chen & Du, 2017; Fan et al., 2019; Fan et al., 2021; Fratescu et al., 2019; Hollingworth & Beck, 2016; King & Macnamara, 2020; B. Zhang et al., 2018; Zhou et al., 2020).

The letters that appeared on the search objects were presented in the center of each object, extending an average of 8 × 10 pixels. There were two target letters: ‘Q’ and ‘P’. One of these (randomly selected) appeared in each search display. The two distractor letters were ‘C’ and ‘R’. These were randomly assigned to the two remaining search objects. When there was a search object that matched features in memory, the target letter either appeared on that object (*valid* condition) or on one of two the mismatching objects (*invalid* condition). The letters were very small so that participants would typically inspect the displays via a series of eye movements (though, of course, we did not monitor gaze position), which was designed to optimize sensitivity to validity effects (Hollingworth & Bahle, 2020a).

The experiment was programmed in Python-based OpenSesame software (Mathôt et al., 2012) and converted to Javascript, using the OSWeb toolbox, for web-based delivery. A JATOS server maintained by the University of Iowa managed online presentation and data collection. After signing up for the study, participants followed a web link to a server address hosting the experiment. They first provided informed consent. They were then given instructions about how to optimize online performance: (a) find a location with minimal distraction, (b) take breaks when needed but complete the experiment in a single session, (c) put the browser into “full screen” mode, and (d) close other browser or app windows. They then received instructions specific to the experimental task.

The sequence of events in a trial is illustrated in Figure 1A.Participants were instructed to rest their thumbs on the spacebar, their left index finger on the ‘Q’ key, and their right index finger on the ‘P’ key. Each trial began with a display instructing participants to “Press SPACEBAR to start next trial” (not pictured in Figure 1A). After doing so, there was a 300-ms delay (fixation dot only), followed by presentation of the memory sample display for 900 ms, a 700-ms ISI, the search array until response, a 200-ms ISI, and the memory test display until response. Participants were instructed to respond to the search task as quickly and accurately as possible and to respond as accurately as possible to the memory test. For the search task, participants pressed the ‘Q’ or ‘P’ key to indicate target identity. For the memory test, they used the same keys to indicate whether the orientations were the same (‘Q’ key) or one had changed (‘P’ key). Feedback was provided for the memory task to encourage participants to maintain the memory sample across the trial (not pictured in Figure 1A). Trials with a correct memory test response were immediately followed by a “smiley” face icon (character U + 1F603) for 200 ms. Trials with an incorrect memory response were followed by a “neutral” face icon (character U + 1F611) for 400 ms. Feedback was not provided for the search task.

Participants first completed a practice block of 20 trials. Next, they completed nine blocks of experimental trials. Each block contained 40 trials: 16 trials in the neutral condition and 24 trials in the match conditions. The 24 match trials in a block were evenly split between same-object-match and different-object-match. Within these sets of 12 trials, four were in the valid condition and eight in the invalid condition. Thus, when there was a matching object, the target letter was no more likely to appear on that object than on either of the two nonmatching objects: memory match did not predict target location. Finally, within the set of 24 match trials in a block, half presented the matching shape in the remembered orientation and half in a changed orientation. Within a block, trials from the various conditions were randomly intermixed. Participants completed a total of 360 experimental trials. The entire experiment lasted approximately 45 min.

Data Analysis

Data from all experiments are available online in an Open Science Framework repository (https://osf.io/gkvnb/). Mean accuracy on the search task was uniformly high (see Table 1). There was no reliable effect of match condition (neutral, same object, different object), $F(2, 86) = .541$, $p = .584$, adj $\eta_p^2 = -.011$.[1] For the two match conditions, there was also no effect of validity on search accuracy, $F(1, 43) = 2.76$, $p = .104$, adj $\eta_p^2 = .038$.

Mean accuracy data for the memory task are reported in Table 1. There was no reliable effect of match condition (neutral, same object, and different object), $F(2, 86) = 1.04$, $p = .359$, adj $\eta_p^2 =$

---

[1] We report adjusted η^2, which removes the positive bias inherent in standard η^2 (Mordkoff, 2019).

Table 1

Mean Search Accuracy and Memory Accuracy for Experiment 1

Measure	Neutral	Same object match		Different object match	
		Valid	Invalid	Valid	Invalid
Search accuracy	0.973 (.004)	0.976 (.005)	0.965 (.006)	0.973 (.006)	0.971 (.004)
Memory accuracy	0.854 (.014)	0.848 (.016)	0.848 (.016)	0.843 (.017)	0.844 (.015)

Note. Standard errors of the means are in parentheses.

.001. For the two match conditions, there was also no effect of validity, $F(1, 43) = .020$, $p = .889$, adj $\eta_p^2 = -.023$. Finally, there was no effect of whether the matching shape feature in the search display was presented in the same or in a changed orientation relative to the sample, display, $t(43) = .294$, $p = .770$, adj $\eta_p^2 = -.021$, with mean accuracy of .845 on the memory test when the orientation in the search display matched the sample orientation and .847 when it did not.

The analysis of RT was limited to correct search trials. To eliminate the extreme outliers possible in an unsupervised experiment, we first eliminated trials with RT less than 200 ms (not plausibly based on target identity) and trials with RT greater than 8,000 ms. Trials were further eliminated if an RT value was more than 2.5 *SD* from a participant's mean in each of the three cuing conditions (valid, invalid, and neutral). Accuracy and outlier trimming led to the elimination of 5.47% of trials. The RT analyses included both memory correct and incorrect trials, because the memory test required different information (orientation) than was required to guide attention. Note that RT analyses limited to memory correct trials produced the same pattern of results and statistical significance as the full RT analyses, reported below.

Results

The primary analysis concerned mean manual RT on the search task as a function of object match and validity (Figure 1C). The match condition data were entered into a 2 (same-object-match, different-object-match) × 2 (valid, invalid) repeated measures analysis of variance. First, there was a reliable main effect of validity, $F(1, 43) = 36.3$, $p < .001$, adj $\eta_p^2 = .445$, with lower mean RT for valid trials (1,229 ms) than for invalid trials (1,323 ms). Note that this effect was not only numerically large (94 ms) but was also observed consistently (across 38 of the 44 participants). Thus, there should have been ample opportunity to observe a modulation of guidance by object structure, if such modulation had been present. There was no main effect of same/different object match, $F(1, 43) = 1.97$, $p = .168$, adj $\eta_p^2 = .022$. Critically, there was no reliable interaction between object match and validity, $F(1, 43) = 1.24$, $p = .272$, adj $\eta_p^2 = .005$. The validity effect was no larger in the same-object-match condition (84 ms) than in the different-object-match condition (104 ms); both validity effects were statistically reliable ($t(43) = 4.66$, $p < .001$, adj $\eta_p^2 = .321$ and $t(43) = 5.85$, $p < .001$, adj $\eta_p^2 = .430$, respectively). To further explore this null effect, we calculated the one-sided Bayes Factor for the contrast in validity effect magnitude between the same- and different-object-match conditions, using the method outlined by Rouder et al. (2009) and the BayesFactor package in R. The test was one sided, because the alternative hypothesis is that the validity effect should have been larger in the same-object-match condition. The Bayes Factor analysis indicated that the data were 12 times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 12.0$).

We conducted two secondary analyses. The first examined whether there were both costs and benefits of VWM match. Collapsing across same/different object match, RT was reliably lower in the valid condition than in the neutral condition, $t(43) = 3.77$, $p < .001$, adj $\eta_p^2 = .231$, and reliably higher in the invalid condition than in the neutral condition, $t(43) = 4.61$, $p < .001$, adj $\eta_p^2 = .315$. The second examined whether there was an effect of same/changed orientation in the search display, which could indicate guidance by remembered orientation. Again collapsing across same/different object match, the magnitude of the validity effect did not differ as a function of same/changed orientation, $F(1, 43) = 1.62$, $p = .210$, adj $\eta_p^2 = .014$, consistent with our assumption that there would be minimal guidance on the basis of remembered orientation (Hulleman, 2020).

Discussion

We observed robust guidance of attention by the contents of VWM in a search paradigm in which remembered features did not predict the target location. However, this guidance was no larger when the two matching features came from the same object in VWM versus from two different objects in VWM. Thus, the results are consistent with a model of VWM in which feature values belonging to an object are maintained separately and have independent effects on the guidance of attention.

One possible concern with this design is that the guidance of attention may have been dominated by only one of the two feature dimensions. For example, if only color match influenced attention, that would also have produced equivalent guidance in the same- and different-object match conditions, as there was one color match to memory in both conditions. To confirm that both color and shape guide attention in this paradigm, we ran a control experiment (Figure 1D). This experiment was identical to Experiment 1, except that when there was a match to memory, the match was only on a single dimension. Specifically, in the *shape-match* condition, one search object matched the shape of one of the two memory items (but neither of the colors). In the *color-match* condition, one of the search objects matched the color of one the two memory items (but neither of the shapes). This allowed us to assess guidance by the two dimensions independently.

Fifty-six new participants (18–30 years old) completed the control experiment, with 42 meeting inclusion criteria.[2] Mean accuracy data on the search and memory tasks are reported in Table 2.[3] For the RT analysis, 5.46% of the data was eliminated based on the criteria used in Experiment 1. The RT data are reported in Figure 1E. The match condition data were entered into a 2 (shape match, color match) × 2 (valid, invalid) repeated measures ANOVA. First, there was a reliable main effect of validity, $F(1, 41) = 10.0$, $p = .003$, adj $\eta_p^2 = .176$, with lower mean RT for valid trials (1,181 ms) than for invalid trials (1,211 ms). There was no main effect of shape/color match, $F(1, 41) = .264$, $p = .610$, adj $\eta_p^2 = -.018$, and no reliable interaction between these factors, $F(1, 41) = .056$, $p = .815$, adj $\eta_p^2 = -.023$. The validity effect was reliable in both the shape-match condition, $t(41) = 2.52$, $p = .016$, adj $\eta_p^2 = .113$, and in the color-match condition, $t(41) = 2.17$, $p = .036$, adj $\eta_p^2 = .081$. Thus, the control experiment indicates that both shape match and color match guide attention in this paradigm, with broadly equivalent validity effects. Further, we examined whether the validity effect in the control experiment was reliably reduced relative to that in the main Experiment 1. Such an effect would indicate greater guidance by two feature matches (main experiment) versus just one (control experiment). The validity effect data from Experiment 1 were collapsed across same- and different-object-match, and the validity effect data from the Experiment 1 control were collapsed across shape and color match. The mean validity effect was reliably larger in Experiment 1 (94 ms) than in the Experiment 1 control (30 ms), $t(84) = 3.45$, $p < .001$, adj $\eta_p^2 = .114$, consistent with guidance by both shape and color in the main experiment.

Experiment 2

In Experiment 1, the memory task did not require explicit feature binding; it could have been completed by remembering features independently of objects. This is actually a common property of experiments probing binding in VWM. For example, the original studies supporting a direct binding model (Luck & Vogel, 1997; Vogel et al., 2001) did not explicitly require memory for binding. And the original studies supporting an indirect binding model also did not require memory for binding (Kahneman et al., 1992; Wheeler & Treisman, 2002). In both hypotheses, features from an object are proposed to be bound (directly or indirectly) as an automatic consequence of attending to the object and encoding it into VWM. Nevertheless, to provide an even stronger test of possible object-based guidance, we modified the paradigm in Experiment 2 so that the memory task strongly encouraged participants to maintain feature bindings in VWM.

Method

Participants

Seventy-one new participants (18–30 years old) were recruited from the University of Iowa undergraduate subject pool and participated for course credit. Participants were excluded based on the same criteria as used in Experiment 1. Forty-one participants met inclusion criteria. Of these 41, 23 were female, 15 were male, and three did not report gender. The larger proportion of eliminated participants in this experiment was driven by increased difficulty of the memory task, as described below.

Stimuli and Procedure

The stimuli and procedure were the same as in Experiment 1, except that the memory task was modified to require memory for shape-color bindings (Figure 2A). Participants were instructed to remember the two combinations of shape and color. All object shapes were presented in the 45° orientation, since there was no longer an orientation memory component to the task.

For the design of the memory test, it is nontrivial to ensure that participants must remember shape-color bindings and also that they must remember both of the two objects. For example, a design in which a "changed" test display constituted two objects with a recombination of features could be solved perfectly by memory for only one of the two objects. Limiting the test array to a single object (same binding or features swapped) is subject to a similar problem. To illustrate this, imagine that the memory array consists of a blue leaf and a red paddle (Figure 2A). The participant only encodes the blue leaf. If the single test item has both remembered features (blue leaf), the participant responds "same." If it has neither (red paddle), the participant also responds "same." If it has only one of the remembered features (blue paddle or red leaf), the participant responds "changed." Thus, a simple rule would potentially produce optimal performance based on memory for only one object: If the test object has just one of the two remembered features, respond "changed"; otherwise, respond "same." To eliminate this possibility, a test condition is needed in which a change is introduced by adding a feature value that was not present in the memory array (e.g., a yellow leaf). Then, if one remembers only one object, there will be trials in which neither test feature matches memory, but the correct response is not "same."

This design was implemented as follows. One test object was displayed at the end of each trial. The test object was either the same as one of the two memory sample objects (same response), it was a recombination of two of the originally displayed feature values (changed response), or it consisted of one remembered value and a new value (shape or color) that had not appeared in the memory sample array (changed response). On each trial, the test condition was randomly selected from these three possibilities, leading to approximately one-third of trials in each condition. In the same condition, the test object was randomly selected from the two possibilities, and it appeared at its original location. In the recombined change condition, the test object was chosen randomly from the two possible recombinations, and location was selected randomly from the two possibilities. Finally, in the change condition with one old and one new feature value, the old value was chosen randomly from the set of four possible remembered values. The new value was selected randomly from the three remaining values on the complementary dimension (i.e., those that had not been used in the memory sample display). The test object appeared at the location originally occupied by the old feature value.

The search task was identical to that in Experiment 1, except all objects appeared in the 45° orientation.

As in Experiment 1, participants completed nine blocks of experimental trials. Each block contained 40 trials: 16 trials in the neutral condition, 12 in the same-object-match condition, and 12

---

[2] Due to a coding error, gender was not recorded for 27 of these 42 participants. For the remaining 15, 11 were female, and four were male.

[3] For search task accuracy, there was no reliable effect of match condition (neutral, shape match, color match), $F(2, 82) = 0.864$, $p = .425$, adj $\eta^2 = -.003$. For the two match conditions, there was also no effect of validity on search accuracy, $F(1, 41) = 0.222$, $p = .640$, adj $\eta^2 = -.019$. For memory task accuracy, there was no reliable effect of match condition (neutral, shape match, color match), $F(2, 82) = 0.843$, $p = .393$, adj $\eta^2 = -.002$. For the two match conditions, there was no effect of validity on memory accuracy, $F(1, 41) = .003$, $p = .960$, adj $\eta^2 = -.024$.

Table 2

Mean Search Accuracy and Memory Accuracy for the Experiment 1 Control Experiment

Measure	Neutral	Shape match		Color match	
		Valid	Invalid	Valid	Invalid
Search accuracy	0.970 (.005)	0.964 (.005)	0.967 (.006)	0.973 (.005)	0.967 (.006)
Memory accuracy	0.857 (.012)	0.859 (.013)	0.851 (.014)	0.845 (.016)	0.852 (.012)

Note. Standard errors of the means are in parentheses.

in the different-object-match. Within these sets of 12 trials, four were in the valid condition and eight in the invalid condition. There was no manipulation of match between memory and search orientations, as all objects appeared in the 45° orientation.

Data Analysis

Mean accuracy on the search task was uniformly high (see Table 3). There was no reliable effect of match condition (neutral, same object, different object), $F(2, 80) = .282$, $p = .755$, adj $\eta_p^2 = -.018$. For the two match conditions, there was also no effect of validity on search accuracy, $F(1, 40) = 1.56$, $p = .219$, adj $\eta_p^2 = .014$.

Mean memory test accuracy was .759 (*SEM* = .022) for the same condition, .821 (*SEM* = .017) for the recombination change condition, and .851 (*SEM* = .014) for the new feature change condition. Mean memory accuracy as a function of the search conditions is reported in Table 3, collapsing across the three test types. There was no reliable effect of match condition (neutral, same object, different object), $F(2, 80) = .44$, $p = .643$, adj $\eta_p^2 = -.014$. For the two match conditions, there was a reliable effect of validity, $F(1, 40) = 7.79$, $p = .008$, adj $\eta_p^2 = .142$, with higher mean accuracy in the valid condition (.825) than in the invalid condition (.801), but this effect did not interact with same-/different-object, $F(1, 40) = .682$, $p = .008$, adj $\eta_p^2 = -.021$.

For the RT analyses, 5.49% of trials was eliminated using the same criteria as in Experiment 1. As in Experiment 1, the RT analyses included both memory correct and incorrect trials. Analyses limited to memory correct trials produced the same pattern of results and statistical significance as the full RT analyses, reported below.

Results

The mean manual RT results are illustrated in Figure 2B. The match condition data were entered into a 2 (same-object-match, different-object-match) × 2 (valid, invalid) repeated measures ANOVA. First, there was a reliable main effect of validity, $F(1, 40) = 92.2$, $p < .001$, adj $\eta_p^2 = .689$, with lower mean RT for valid trials (1,412 ms) than for invalid trials (1,616 ms).

There was no main effect of same/different object match, $F(1, 40) = 0.931$, $p = .340$, adj $\eta_p^2 = -.001$. Critically, there was no reliable interaction between these factors, $F(1, 40) = 1.69$, $p = .201$, adj $\eta_p^2 = .017$. The mean validity effect was 218 ms in the same-object-match condition and 191 ms in the different-object-match condition; both validity effects were statistically reliable ($t(40) = 8.39$, $p < .001$, adj $\eta_p^2 = .628$ and $t(40) = 9.01$, $p < .001$, adj $\eta_p^2 = .662$, respectively).[4] The one-sided Bayes Factor analysis indicated that the data were 1.5 times more likely to have been generated by the alternative model than by the null model ($BF_{01} = 0.66$). Thus, although we cannot draw strong conclusions in favor of the null model from this experiment, the data also provide no strong evidence to support an object-based advantage.

In addition to this main analysis, we again examined whether there were both costs and benefits of VWM match. Collapsing across same/different object match, RT was reliably lower in the valid condition than in the neutral condition, $t(40) = 6.80$, $p < .001$, adj $\eta_p^2 = .524$, and reliably higher in the invalid condition than in the neutral condition, $t(43) = 4.27$, $p < .001$, adj $\eta_p^2 = .296$.

Discussion

In Experiment 2, we created conditions that should have been highly conducive to observing a same-object advantage, had it been present. First, we tested the modulation of a validity effect that was both numerically robust (on the order 200 ms) and observed consistently (across 40 of the 41 participants). Second, the memory paradigm strongly encouraged strategic maintenance of bound object representations, and it could not have been performed optimally without such representations. Yet, there was no strong evidence to indicate that attention guidance was more robust when the matching search item was identical to a remembered object than when it matched features drawn from different remembered objects. To further quantify the relative evidence for the presence/absence of a same-object advantage, we conducted the Bayes factor analysis over the combined data from Experiments 1 and 2. Under the theories for which we are generating predictions, feature binding (whether direct or indirect) is an automatic consequence of VWM encoding; from this perspective, the two experiments are essentially identical. The combined data were 7 times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 6.99$).

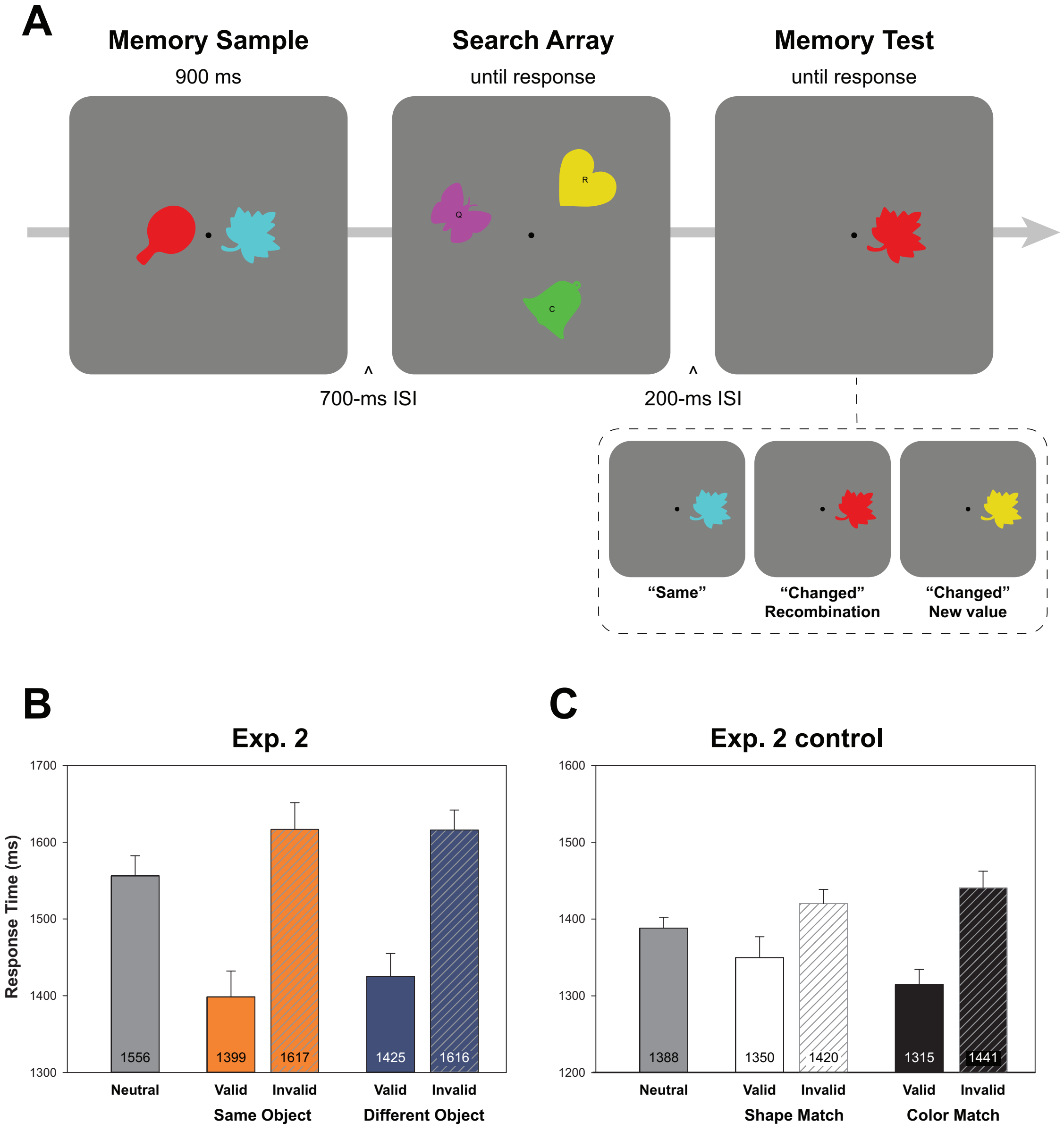
As in Experiment 1, it is important to ensure that both color and shape guide attention in this version of paradigm. Thus, we ran another control experiment that was identical to Experiment 2, except that when there was a match to memory, the match was only on a single dimension (color or shape). Sixty-five new participants completed the control experiment, with 41 meeting inclusion criteria (20 female, 17 male, and four not reporting). Mean accuracy data on the search and memory tasks are reported in Table 4.[5] For the RT analysis,

---

[4] The larger validity effect in Experiment 2 compared with Experiment 1 is consistent with a known difference between attention guidance by task-relevant versus incidental features, with the former generating more robust guidance (e.g., Hollingworth & Luck, 2009).

[5] For search task accuracy, there was a reliable effect of match condition (neutral, shape match, color match), $F(2, 80) = 4.43$, $p = .015$, adj $\eta^2 = .089$, with mean accuracy of .972 in the neutral condition, .976 in the shape-match condition, and .981 in the color-match condition. Given that the RT results concerned validity effects within each dimension, this difference does not impact interpretation the main RT analyses. For the two match conditions, there was no effect of validity on search accuracy, $F(1, 40) = 0.765$, $p = .387$, adj $\eta^2 = -.006$. For memory task accuracy, there was no reliable effect of match condition (neutral, shape match, color match), $F(2, 80) = 0.088$, $p = .916$, adj $\eta^2 = -.023$. For the two match conditions, there was no effect of validity on memory accuracy, $F(1, 40) = .152$, $p = .699$, adj $\eta^2 = -.021$.

Figure 2
Experiment 2 Design and Results



Note. (A) Design and sequence of events in a trial of Experiment 2. Participants remembered the two feature combinations in the memory sample display. In the memory test display, one test item was presented that was either the same as one of the two memory items, changed via recombination of features from the sample display, or changed via the addition of one feature value that had not appeared in the sample display. The search task and condition structure was same as in Experiment 1 (illustrated in Figure 1B). (B) Mean response time (RT) in Experiment 2 as a function of match condition and validity. (C) In a control experiment, matches to memory in the search display were only on a single dimension (see Figure 1D). Mean RT in the Experiment 2 control is displayed as a function of match condition and validity. In Panels B and C, the values represented by the bars are inset at the base of each bar. Error bars are condition-specific, within-subject 95% confidence intervals (Morey, 2008). See the online article for the color version of this figure.

5.17% of the data was eliminated based on the criteria used in Experiment 1. The RT results are reported in Figure 2C. The match condition data were entered into a 2 (shape match, color match) × 2 (valid, invalid) repeated measures ANOVA. First, there was a reliable main effect of validity, $F(1, 40) = 58.3$, $p < .001$, adj $\eta_p^2 = .583$, with lower mean RT for valid trials (1,332 ms) than for invalid trials (1,430 ms). There was no main effect of shape/color match, $F(1, 40) = .655$, $p = .423$, adj $\eta_p^2 = -.009$. However, these factors reliably interacted, $F(1, 40) = 6.25$, $p = .017$, adj $\eta_p^2 = .113$, with a larger validity effect for color match (126 ms) than for shape match (70 ms). This difference between the two dimensions was expected. The Experiment 1 method (orientation memory) was

Table 3

Mean Search Accuracy and Memory Accuracy for Experiment 2

Measure	Neutral	Same object match		Different object match	
		Valid	Invalid	Valid	Invalid
Search accuracy	0.972 (.005)	0.974 (.006)	0.973 (.004)	0.977 (.005)	0.972 (.005)
Memory accuracy	0.813 (.015)	0.827 (.017)	0.807 (.016)	0.822 (.016)	0.796 (.016)

Note. Standard errors of the means are in parentheses.

designed to reduce the inherent difference in guidance between color and shape; this compensation was not used in Experiment 2, and thus the standard advantage for guidance by color was observed. Critically, however, the validity effect was statistically reliable in both the color-match condition, $t(40) = 7.94$, $p < .001$, adj $\eta_p^2 = .601$, and in the shape-match condition, $t(40) = 3.91$, $p < .001$, adj $\eta_p^2 = .258$. Thus, the control experiment indicates that both shape match and color match guide attention in this version of paradigm.

Further, we examined whether the validity effect in the control experiment was reliably reduced relative to that in the main Experiment 2. Such an effect would again indicate greater guidance by two feature matches (main experiment) versus just one (control experiment). The validity effect data from Experiment 2 were collapsed across same- and different-object-match and were compared with the larger of the two validity effects (color) from the Experiment 2 control. The mean validity effect was reliably larger in Experiment 2 (206 ms) than in the color match condition of the Experiment 2 control (126 ms), $t(80) = 2.96$, $p = .004$, adj $\eta_p^2 = .088$, consistent with guidance by both shape and color in the main experiment.

Experiment 3

So far, we have examined the guidance of attention by VWM under conditions where remembered feature values did not predict the target of search, and thus participants had no incentive to guide attention strategically. However, strategic control from VWM is central to theories of attention and visual search (Bundesen, 1990; Desimone & Duncan, 1995; Hamker, 2005; Wolfe, 1994), and feature templates supporting strategic selection are indeed maintained in VWM when the cued values change from trial-to-trial (e.g., Carlisle et al., 2011), as here. Thus, it is important to test broad questions about the relationship between VWM and attention in the contexts of both incidental and strategic guidance (see, e.g., Bahle et al., 2020; Hollingworth & Bahle, 2020b). In Experiments 3A and 3B, the paradigm was modified to probe the strategic guidance of attention from VWM and its potential modulation by object structure (Figure 3A). In both subexperiments, the participants had incentive to use the memory display (now termed the *cue display*) as a template for visual search. Because the search task itself created a demand to maintain the objects in VWM, the end-of-trial memory test was no longer necessary and was eliminated from the paradigm.

The search task in Experiment 3A was the same as in Experiments 1 and 2, except invalid trials were eliminated. On 60% of trials, a cue-matching object was present in the display (same- or different-object-match), and this object always contained the target letter, providing incentive to search strategically for matching objects. The remaining 40% were neutral trials, in which no cue-matching features were present. In Experiment 3B, we introduced a stronger manipulation, in which selection based on memory was *required* to perform the search task. Neutral trials were also eliminated, and all three search objects contained a possible target letter (Q or P). Thus, participants were required to find the search object that matched a cued feature and report the identity of the letter superimposed upon it. The simplicity of this design allowed us to integrate single-feature control conditions (as in the Experiment 1 and 2 control experiments) into the main body of Experiment 3B. Specifically, there were four conditions: same-object match, different-object match, shape match, and color match, as illustrated in Figure 3A. In both experiments, we expected robust guidance from VWM, and, in Experiment 3B, we expected more efficient guidance with two matching features than with only one (as in the comparisons between Experiments 1 and 2 and their respective control experiments). The critical contrast in both experiments was search time between the same-object and different-object match conditions.

Method

Participants

One hundred and five participants (18–30 years old; 46 in Experiment 3A and 59 in Experiment 3B) were recruited from the University of Iowa undergraduate subject pool and participated for course credit. Participants were excluded if less than 80% of their trials would have been used in the RT analysis. Forty-five participants met the inclusion criterion for Experiment 3A (35 female and 10 male). Forty-one met the inclusion criterion for Experiment 3B (20 female, 18 male, and three not reporting).

Table 4

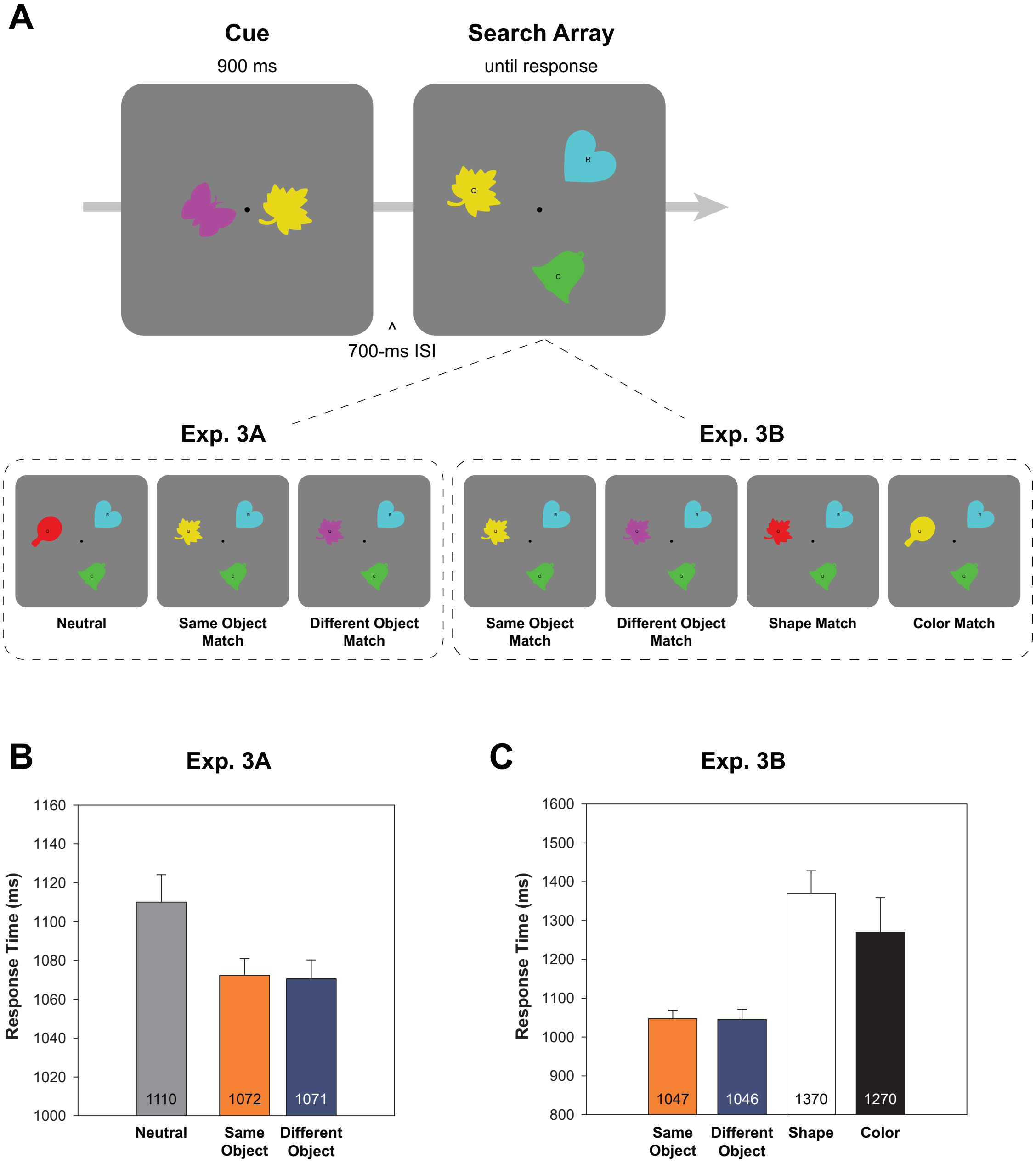
Mean Search Accuracy and Memory Accuracy for the Experiment 2 Control Experiment

Measure	Neutral	Shape match		Color match	
		Valid	Invalid	Valid	Invalid
Search accuracy	0.972 (.003)	0.972 (.006)	0.979 (.003)	0.981 (.004)	0.980 (.004)
Memory accuracy	0.803 (.016)	0.797 (.018)	0.805 (.017)	0.811 (.016)	0.797 (.017)

Note. Standard errors of the means are in parentheses.

Figure 3

Experiment 3 Design and Results



Note. (A) Design and sequence of events in a trial of Experiments 3A and 3B. The method was the same as in Experiment 2, except the colored shapes in the cue display predicted the location of the target letter, as invalid trails were eliminated. Moreover, In Experiment 3B the neutral trials were also eliminated, and each object contained a possible target letter (‘Q’ or ‘P’), forcing participants to use the cued features to find the matching object and report the identity of the superimposed letter. The memory test at the end of the trial was eliminated in both experiments. (B) Mean response time (RT) in Experiment 3A as a function of match condition. (C) Mean RT in Experiment 3B as a function of match condition. The values represented by the bars are inset at the base of each bar. Error bars are condition-specific, within-subject 95% confidence intervals (Morey, 2008). See the online article for the color version of this figure.

Stimuli and Procedure

The stimuli and procedure were the same as in Experiments 1 and 2, with the following exceptions. First, all object shapes were presented in the 45° orientation, as there was no orientation memory component to the task. In addition, the end-of-trial memory test was eliminated: Each trial consisted of a cue display and a search display, separated by a 700-ms ISI.

The search task in Experiment 3A was the same as in Experiments 1 and 2, except the invalid condition was eliminated. Each block contained 40 trials: 16 trials in the neutral condition and 24 trials in which a matching object was presented that contained the target letter: 12 in the same-object-match condition and 12 in the different-object-match condition.

The search task in Experiment 3B was modified so that cue information was required to execute the appropriate response. Each search display contained one object that matched either one of the feature values from the cue display (shape or color) or two of the values (from the same object or from different objects). Each of the three objects in the search array contained a potential target letter (Q or P). In a given display, there were always two examples of one target letter and one of the other (i.e., two Qs and one P or two Ps and one Q, randomly selected). The cue-matching object could either contain the only example of that letter in the display or one of two examples. This was randomly selected on each trial so that letter ratio did not predict the correct response. Participants were instructed to find the one object in the search array that matched either of the two cued colors or either of the two cued shapes and to report the identity of the letter on that object. Each of the 12 experimental blocks contained 40 trials, with 10 in each of the four conditions: same-object match, different-object match, shape match, and color match.

Participants completed a total of 360 experimental trials in Experiment 3A and 480 trials in experiment 3B.

Data Analysis

For Experiment 3A, mean search accuracy did not differ as a function of match condition, $F(2, 88) = .388$, $p = .680$, adj $\eta_p^2 = -.014$, with mean accuracy of .969 (*SE* = .004) in the neutral condition, .970 (*SE* = .004) in the same-object-match condition, and .966 (*SE* = .004) in the different-object-match condition.

For Experiment 3B, mean search accuracy was .922 (*SE* = .006) in the same-object-match condition, .939 (*SE* = .006) in the different-object-match condition, .821 (*SE* = .011) in the shape-match condition, and .862 (*SE* = .011) in the color-match condition. Search accuracy differed across conditions as expected by the fact that, in the same- and different-object match conditions, two remembered features defined the target object, whereas only one did in the two single-feature conditions. There was a reliable effect of the number of matching features, with higher accuracy in the same- and different-object match conditions than in the two single-feature conditions, $F(1, 40) = 165.3$, $p < .001$, adj $\eta_p^2 = .800$. For the object-match conditions, there was also a reliable difference in search accuracy, $t(40) = 2.71$, $p = .010$, adj $\eta_p^2 = .135$, with higher accuracy in the different-object-match condition than in the same-object-match condition, an effect in the reverse direction than predicted by an object-based guidance hypothesis. Finally, for the two single-feature conditions, accuracy was higher in the color-match condition than in the shape-match condition, $t(40) = 2.18$, $p = .035$, adj $\eta_p^2 = .084$, consistent the expectation of more robust guidance by color than by shape (see Experiment 2).

For the RT analysis, accuracy and outlier trimming led to the elimination of 4.89% of trials in Experiment 3A and 14.3% of trials in Experiment 3B (with the higher proportion due to lower accuracy).

Results and Discussion

Experiment 3A

RT results are presented in Figure 2B. There was a robust effect of memory match. Mean RT in the same-object-match condition was reliably lower than that in the neutral condition, $t(44) = 4.38$, $p < .001$, adj $\eta_p^2 = .288$, and RT in the different-object-match condition was also reliably lower than that in the neutral condition, $t(44) = 4.32$, $p < .001$, adj $\eta_p^2 = .282$. Critically, there was no reliable RT difference between the same- and different-object-match conditions, $t(44) = .386$, $p = .701$, adj $\eta_p^2 = -.020$. The one-sided Bayes Factor analysis (H1 = lower RT for same- than for different-object match) indicated that the data were eight times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 8.13$).

One possible concern with this analysis is that some participants may have ignored the cue information, limiting sensitivity to differential guidance as a function of object match. To examine this, we probed whether there was a positive relationship between the magnitude of the overall cuing effect (neutral—match, collapsing across same/different object) and the magnitude of a possible same-object advantage (different—same). There was no evidence to indicate that the participants who used the cue more effectively to guide search exhibited a same-object advantage, with a nonreliable trend in the reverse direction, $r = -.12$, $t(44) = -.793$, $p = .432$.

Experiment 3B

First, there was a reliable effect of the number of matching features in the display, with lower RT in the same- and different-object-match conditions (in which the target was defined by both shape and color match) compared with the two single-feature conditions (shape and color), $F(1, 40) = 203.3$, $p < .001$, adj $\eta_p^2 = .832$. This effect remained reliable when the object-match conditions were compared against the faster of the two single-feature conditions (color), $t(40) = 4.84$, $p < .001$, adj $\eta_p^2 = .353$. These results indicate that both feature dimensions were used to guide search in the same- and different-object-match conditions. For the single-feature control conditions, there was a nonreliable trend toward lower RT in the color-match condition than in the shape-match condition, $t(40) = 1.62$, $p = .113$, adj $\eta_p^2 = .039$, with the direction of the trend consistent with the expectation that color would provide more robust guidance than shape (see Experiment 2).

The critical analysis concerned the contrast between same- and different-object match. There was no reliable RT difference between these conditions, $t(40) = .184$, $p = .855$, adj $\eta_p^2 = -.024$. The one-sided Bayes Factor analysis (H1 = lower RT for same- than for different-object match) indicated that the data were approximately seven times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 6.79$).

To further quantify the relative evidence for the presence/absence of a same-object advantage, we conducted the Bayes factor analysis over the combined same-/different-object match data from Experiments 3A and 3B. The combined data were 11 times more likely to have been generated by the null model than by the alternative model ($BF_{01} = 11.0$).

In summary, two matching features from two different objects in VWM generated strategic guidance that was no less efficient than two matching features from a single object in VWM, consistent with the hypothesis that guidance from VWM is feature-based, applied independently for each remembered feature value.

General Discussion

In the present study, we asked whether object representations control the interaction between VWM and the guidance of attention.

To this end, we examined whether the guidance of attention by objects matching two features in VWM was modulated by whether the matching features were associated with the same remembered object or with two different remembered objects. In three experiments, two that probed incidental guidance and one that probed strategic guidance, we found robust effects of memory match on the allocation of attention. However, the magnitudes of these effects did not reliably differ between and the same- and different-object-match conditions. The results indicate that the guidance of attention from VWM is largely feature-based, with the combined effect of individual-feature matches generating guidance that is equivalent to that from whole-object matches.

These findings potentially contrast with those from a recent study by Saiki (2016). Saiki asked whether the recognition of feature values maintained in VWM is organized by object structure (see also Saiki, 2019). Participants remembered two objects on a trial, each a color-shape conjunction, as in the present study. Then, they completed a recognition memory test with a single test object. To examine whether multiple remembered feature values simultaneously contribute to a common recognition decision (i.e., coactivate in recognition), the test item matched either one remembered feature value or two. Saiki found robust coactivation by multiple matching features. Critically, coactivation was limited to the condition in which the two values came from the same remembered object; there was no coactivation when the two matching values were drawn from different remembered objects. This contrasts with the present results and, even more directly, with the results of Bahle et al. (2020), who found robust coactivation in the guidance of attention from two features associated with different perceptual objects.

Although Saiki's results could be used to argue for direct feature-to-feature binding in VWM, it is important to note that the data provide no direct support for this conclusion. Features can coactivate in recognition without being bound directly to each other. The only requirement for coactivation is that two sources of information converge to drive a common operation, such as decision or response selection (Miller, 1982; Mordkoff & Yantis, 1991). This could occur under both an integrated features model and an independent stores model. Moreover, the observation of coactivation only when the two features came from the same remembered object could have been driven by retrieval dynamics rather than by direct integration of features. Retrieval and recognition operations have already been shown to be strongly influenced by remembered object location (Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Jiang et al., 2000; Kahneman et al., 1992). If access to VWM representations in Saiki's recognition task was also organized by remembered location, then features associated with the same location would tend to be retrieved at the same time (allowing for coactivation), whereas features associated with different locations would not necessarily be retrieved simultaneously (strongly limiting the possibility of coactivation).[6] In summary, then, a plausible explanation of the differing results is that the Saiki study depended on explicit access to VWM, engaging position-mediated retrieval, whereas the present study probed the effects of VWM on other, ongoing cognitive operations without the demand for retrieval.

It is also informative to compare the present results with those of Berggren and Eimer (2018). In an event-related potential study, they had participants search for two targets, each a conjunction of shape and color. The magnitude and timing of the N2PC component was measured for lateralized stimuli that either matched one of the conjunction targets or was a recombination of features from the two targets, similar to the present design. Berggren and Eimer found that, in one experiment, the magnitude of the N2PC was greater for targets than for distractors composed of recombined target features, potentially consistent with object-based guidance of visual search. Since the two targets in this study were the same throughout the entire experiment, guidance was likely to have depended on long-term memory (Carlisle et al., 2011) rather than VWM, as studied here. The results raise the possibility that with learning, template representations in LTM can be formed that directly bind multiple surface feature attributes into an integrated representation, constituting an important dissociation between long-term templates and VWM. However, it is important to note that Berggren and Eimer observed an effect of object structure in only one of their two experiments, the effect was limited to the late period of the N2PC, and the difference was statistically reliable only after a median split of the data based on an additional theoretical assumption (that only one of the two target templates guided attention at a time). Thus, we consider the issue of object-based guidance from LTM to still need clarification.

In addition to the structure potentially introduced by feature conjunctions, we have recently tested whether the guidance of attention from VWM is influenced by structure imposed by the locations of remembered objects. In Hollingworth and Bahle (2020b; see also van Moorselaar et al., 2014), participants remembered an object with an incidental color in preparation for a memory test at the end of the trial. In the search array, one item could match the remembered color, this item was either the target or a distractor, and this item either appeared in the original location of the remembered object or in a different location. A match to the remembered color produced both reliable costs (when the matching item was a distractor) and benefits (when the matching item was the target), as in the present study. However, neither effect was modulated by position match, indicating that the guidance operation was not strongly biased by remembered location. This finding suggests that, although features are clearly bound to object locations in VWM (Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Kahneman et al., 1992), the effects of feature maintenance on other processes need not inherit this structure, with the feature-based guidance of attention from VWM implemented globally and independently of remembered location. Moreover, this finding highlights the broad point that, when retrieval demands are minimized in paradigms testing VWM structure, object-based effects tend to be eliminated as well, consistent with the proposal that they are often generated when remembered location is used as a cue to explicitly retrieve associated features.

How might the architecture of VWM maintenance and VWM-based guidance of attention be structured to accommodate the results

---

[6] Note that the lack of a location effect in the Saiki (2016) study (coactivation from features of the same remembered object was observed independently of whether that object was in the remembered location or in a different location) does not provide strong evidence that the features were not bound to location. Again, coactivation requires only that two sources of information are available simultaneously and contribute to a common decision process. It is perfectly possible that features bound to the same location in memory were accessed simultaneously whether or not that location corresponded to the test location.

discussed so far? We believe this requires three basic assumptions. The first is a fundamental division between the mechanisms used to maintain perceptual feature values over time and the mechanisms used to code object location (Kahneman et al., 1992; Schneegans & Bays, 2017). Specifically, in the object-file framework of Kahneman et al. features of objects are indexed by their spatial locations over time, with the representation of the spatiotemporal properties of objects maintained separately from their surface feature properties.[7] A plausible neural instantiation of this distinction would involve the maintenance of surface features within modality-specific (and likely feature-specific) sensory areas (Emrich et al., 2013; Harrison & Tong, 2009; Quentin et al., 2019; Riggall & Postle, 2012; Serences et al., 2009) and the maintenance of spatiotemporal indexes in parietal systems (Hakim et al., 2019; Vogel & Machizawa, 2004) or, perhaps, medial temporal systems (Rolls & Wirth, 2018).

The second assumption is that feature values are maintained independently of each other (Wheeler & Treisman, 2002) and are bound within the same object representation only by virtue of being associated with the same spatiotemporal index. Again, this is a central tenet of the object-file framework. It is consistent with the present finding of insensitivity to object structure in the guidance of attention, and it is consistent with only weak correlations between the report of different feature values associated with the same remembered object (Bays et al., 2011; Fougnie & Alvarez, 2011; Fougnie et al., 2013). Recently, Schneegans and Bays (2017) have formalized this assumption in a model that, among other contributions, grounds the Kahneman et al. (1992) descriptive model within current understanding of neural information processing. In addition to this basic assumption of feature independence, we assume that sustained activation in sensory areas is implemented in a spatially global manner, with sensory activation generalizing to retinotopically tuned populations coding locations other than that occupied by the encoded object (Ester et al., 2009).

The third assumption is that a key locus of attentional guidance from VWM occurs at a sensory level. Specifically, sustained activity in feature-specific sensory systems (Emrich et al., 2013; Harrison & Tong, 2009; Riggall & Postle, 2012; Serences et al., 2009) filters new sensory input to enhance the response to stimuli that match the content of VWM, thereby biasing attention toward locations containing matching features (Hollingworth et al., 2013a, 2013b). With no direct association between the activity of feature values belonging to the same object, such guidance would be implemented in a manner that was largely insensitive to object structure, as observed here; guidance would be primarily feature-based and not object-based. Moreover, with spatially global activity, attentional guidance would also be applied in a spatially global manner (Martinez-Trujillo & Treue, 2004; W. Zhang & Luck, 2009) and independently of the original location of the remembered object (Hollingworth & Bahle, 2020b; van Moorselaar et al., 2014).

Conclusion

In summary, we propose that object-based effects in VWM tasks typically arise at encoding (via consolidation that is mediated by spatial attention) or in the course of explicit access (via the use of location as a retrieval cue) but that features from the same object are maintained independently of each other and are bound only indirectly through shared spatial location (Kahneman et al., 1992). Thus, if an operation involving VWM does not place strong demands on access/retrieval, as in the present study, then individual feature values can influence other cognitive operations in a manner that is largely independent of object structure. This would allow a person to encode object representations (by attending to an object and binding feature values to shared location) to remember those objects (by maintaining this binding structure over time) and to systematically retrieve information belonging to the same object (by position-mediated retrieval) but to guide attention globally and in a purely feature-based manner, via direct interaction between the independent sensory activation of feature values and new perceptual input.

---

[7] Note that this should not be taken to suggest that the remembered feature values can be accessed only by reference to location or that retrieval based on location will necessarily be the dominant mode of access. A large set of studies indicates that surface features of objects play an important role in establishing object correspondence and continuity (Hein & Moore, 2012; Hollingworth & Franconeri, 2009; Hollingworth et al., 2008; Moore et al., 2010; Richard et al., 2008).

References

Alexander, R. G., Nahvi, R. J., & Zelinsky, G. J. (2019). Specifying the precision of guiding features for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1248–1264. https://doi.org/10.1037/xhp0000668

Bahle, B., Beck, V. M., & Hollingworth, A. (2018). The architecture of interaction between visual working memory and visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(7), 992–1011. https://doi.org/10.1037/xhp0000509

Bahle, B., & Hollingworth, A. (2019). Contrasting episodic and template-based guidance during search through natural scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(4), 523–536. https://doi.org/10.1037/xhp0000624

Bahle, B., Thayer, D. D., Mordkoff, J. T., & Hollingworth, A. (2020). The architecture of working memory: Features from multiple remembered objects produce parallel, coactive guidance of attention in visual search. *Journal of Experimental Psychology: General*, *149*(5), 967–983. https://doi.org/10.1037/xge0000694

Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual working memory. *Neuropsychologia*, *49*(6), 1622–1631. https://doi.org/10.1016/j.neuropsychologia.2010.12.023

Beck, V. M., & Hollingworth, A. (2017). Competition in saccade target selection reveals attentional guidance by simultaneously active working memory representations. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(2), 225–230. https://doi.org/10.1037/xhp0000306

Berggren, N., & Eimer, M. (2018). Object-based target templates guide attention during visual search. *Journal of Experimental Psychology, Human Perception and Performance*, *44*(9), 1368–1382. https://doi.org/10.1037/xhp0000541

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547. https://doi.org/10.1037/0033-295X.97.4.523

Bundesen, C., Habekost, T., & Kyllingsbaek, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review*, *112*(2), 291–328. https://doi.org/10.1037/0033-295X.112.2.291

Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *The Journal of Neuroscience*, *31*(25), 9315–9322. https://doi.org/10.1523/JNEUROSCI.1097-11.2011

Chen, Y., & Du, F. (2017). Two visual working memory representations simultaneously control attention. *Scientific Reports*, *7*(1), 6107. https://doi.org/10.1038/s41598-017-05865-1

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. https://doi.org/10.1146/annurev.ne.18.030195.001205

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*(4), 501–517. https://doi.org/10.1037/0096-3445.113.4.501

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458. https://doi.org/10.1037/0033-295X.96.3.433

Emrich, S. M., Riggall, A. C., Larocque, J. J., & Postle, B. R. (2013). Distributed patterns of activity in sensory cortex reflect the precision of multiple items maintained in visual short-term memory. *The Journal of Neuroscience*, *33*(15), 6516–6523. https://doi.org/10.1523/JNEUROSCI.5732-12.2013

Ester, E. F., Serences, J. T., & Awh, E. (2009). Spatially global representations in human primary visual cortex during working memory maintenance. *Journal of Neuroscience*, *29*(48), 15258–15265. https://doi.org/10.1523/JNEUROSCI.4388-09.2009

Fan, L. X., Sun, M. D., Xu, M. S., Li, Z. A., Diao, L. T., & Zhang, X. M. (2019). Multiple representations in visual working memory simultaneously guide attention: The type of memory-matching representation matters. *Acta Psychologica*, *192*, 126–137. https://doi.org/10.1016/j.actpsy.2018.11.005

Fan, L. X., Xu, M. S., ul Hasan, N., Sun, M., & Zhang, X. (2021). Attentional guidance from two representations of the same or different dimensions in visual working memory. *Current Psychology*, *40*(1), 355–366. https://doi.org/10.1007/s12144-018-9949-9

Foerster, R. M., & Schneider, W. X. (2018). Involuntary top-down control by search-irrelevant features: Visual working memory biases attention in an object-based manner. *Cognition*, *172*, 37–45. https://doi.org/10.1016/j.cognition.2017.12.002

Fougnie, D., & Alvarez, G. A. (2011). Object features fail independently in visual working memory: Evidence for a probabilistic feature-store model. *Journal of Vision*, *11*(12), 3. https://doi.org/10.1167/11.12.3

Fougnie, D., Cormiea, S. M., & Alvarez, G. A. (2013). Object-based benefits without object-based representations. *Journal of Experimental Psychology: General*, *142*(3), 621–626. https://doi.org/10.1037/a0030300

Fratescu, M., Van Moorselaar, D., & Mathot, S. (2019). Can you have multiple attentional templates? Large-scale replications of Van Moorselaar, Theeuwes, and Olivers (2014) and Hollingworth and Beck (2016). *Attention, Perception, & Psychophysics*, *81*(8), 2700–2709. https://doi.org/10.3758/s13414-019-01791-8

Gao, T., Gao, Z., Li, J., Sun, Z., & Shen, M. (2011). The perceptual root of object-based storage: An interactive model of perception and visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(6), 1803–1823. https://doi.org/10.1037/a0025637

Hakim, N., Adam, K. C. S., Gunseli, E., Awh, E., & Vogel, E. K. (2019). Dissecting the neural focus of attention reveals distinct processes for spatial attention and object-based storage in visual working memory. *Psychological Science*, *30*(4), 526–540. https://doi.org/10.1177/0956797619830384

Hamker, F. H. (2005). The reentry hypothesis: The putative interaction of the frontal eye field, ventrolateral prefrontal cortex, and areas V4, IT for attention and eye movement. *Cerebral Cortex*, *15*(4), 431–447. https://doi.org/10.1093/cercor/bhh146

Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, *458*(7238), 632–635. https://doi.org/10.1038/nature07832

Hein, E., & Moore, C. M. (2012). Spatio-temporal priority revisited: The role of feature identity and similarity for object correspondence in apparent motion. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(4), 975–988. https://doi.org/10.1037/a0028197

Hollingworth, A. (2007). Object-position binding in visual memory for natural scenes and object arrays. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(1), 31–47. https://doi.org/10.1037/0096-1523.33.1.31

Hollingworth, A., & Bahle, B. (2020a). Eye tracking in visual search experiments. In S. Pollmann (Ed.), *Neuromethods: Spatial learning and attention guidance* (pp. 23–35). Springer. https://doi.org/10.1007/7657_2019_30

Hollingworth, A., & Bahle, B. (2020b). Feature-based guidance of attention by visual working memory is applied independently of remembered object location. *Attention, Perception & Psychophysics*, *82*(1), 98–108. https://doi.org/10.3758/s13414-019-01759-8

Hollingworth, A., & Beck, V. M. (2016). Memory-based attention capture when multiple items are maintained in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(7), 911–917. https://doi.org/10.1037/xhp0000230

Hollingworth, A., & Franconeri, S. L. (2009). Object correspondence across brief occlusion is established on the basis of both spatiotemporal and surface feature cues. *Cognition*, *113*(2), 150–166. https://doi.org/10.1016/j.cognition.2009.08.004

Hollingworth, A., & Luck, S. J. (2009). The role of visual working memory (VWM) in the control of gaze during visual search. *Attention, Perception, & Psychophysics*, *71*(4), 936–949. https://doi.org/10.3758/APP.71.4.936

Hollingworth, A., & Matsukura, M. (2019). Feature-based guidance of attention during post-saccadic selection. *Attention, Perception & Psychophysics*, *81*(6), 1822–1835. https://doi.org/10.3758/s13414-019-01719-2

Hollingworth, A., & Rasmussen, I. P. (2010). Binding objects to locations: The relationship between object files and visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(3), 543–564. https://doi.org/10.1037/a0017836

Hollingworth, A., Matsukura, M., & Luck, S. J. (2013a). Visual working memory modulates low-level saccade target selection: Evidence from rapidly generated saccades in the global effect paradigm. *Journal of Vision*, *13*(13), 4. https://doi.org/10.1167/13.13.4

Hollingworth, A., Matsukura, M., & Luck, S. J. (2013b). Visual working memory modulates rapid eye movements to simple onset targets. *Psychological Science*, *24*(5), 790–796. https://doi.org/10.1177/0956797612459767

Hollingworth, A., Richard, A. M., & Luck, S. J. (2008). Understanding the function of visual short-term memory: Transsaccadic memory, object correspondence, and gaze correction. *Journal of Experimental Psychology: General*, *137*(1), 163–181. https://doi.org/10.1037/0096-3445.137.1.163

Hulleman, J. (2020). Quantitative and qualitative differences in the top-down guiding attributes of visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(9), 942–964. https://doi.org/10.1037/xhp0000764

Hyun, J. S., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J. (2009). The comparison of visual working memory representations with perceptual inputs. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(4), 1140–1160. https://doi.org/10.1037/a0015019

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(3), 683–702. https://doi.org/10.1037/0278-7393.26.3.683

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*(2), 175–219. https://doi.org/10.1016/0010-0285(92)90007-O

King, M. J., & Macnamara, B. N. (2020). Three visual working memory representations simultaneously control attention. *Scientific Reports*, *10*(1), 10504. https://doi.org/10.1038/s41598-020-67455-y

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. https://doi.org/10.1038/36846

Marshall, L., & Bays, P. M. (2013). Obligatory encoding of task-irrelevant features depletes working memory resources. *Journal of Vision*, *13*(2), 21. https://doi.org/10.1167/13.2.21

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology*, *14*(9), 744–751. https://doi.org/10.1016/j.cub.2004.04.028

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

Matsukura, M., & Vecera, S. P. (2011). Object-based selection from spatially-invariant representations: Evidence from a feature-report task. *Attention, Perception, & Psychophysics*, *73*(2), 447–457. https://doi.org/10.3758/s13414-010-0039-9

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*(2), 247–279. https://doi.org/10.1016/0010-0285(82)90010-X

Moore, C. M., Stephens, T., & Hein, E. (2010). Features, as well as space and time, guide object persistence. *Psychonomic Bulletin & Review*, *17*(5), 731–736. https://doi.org/10.3758/PBR.17.5.731

Mordkoff, J. T. (2019). A simple method for removing bias from a popular measure of standardized effect size: Adjusted partial eta squared. *Advances in Methods and Practices in Psychological Science*, *2*(3), 228–232. https://doi.org/10.1177/2515245919855053

Mordkoff, J. T., & Yantis, S. (1991). An interactive race model of divided attention. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(2), 520–538. https://doi.org/10.1037/0096-1523.17.2.520

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, *4*, 61–64. https://doi.org/10.20982/tqmp.04.2.p061

Olivers, C. N. L. (2009). What drives memory-driven attentional capture? The effects of memory type, display type, and search type. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1275–1291. https://doi.org/10.1037/a0013896

Olivers, C. N. L., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(5), 1243–1265. https://doi.org/10.1037/0096-1523.32.5.1243

Olson, I. R., & Jiang, Y. (2002). Is visual short-term memory object based? Rejection of the "strong-object" hypothesis. *Perception & Psychophysics*, *64*(7), 1055–1067. https://doi.org/10.3758/BF03194756

Quentin, R., King, J. R., Sallard, E., Fishman, N., Thompson, R., Buch, E. R., & Cohen, L. G. (2019). Differential brain mechanisms of selection and maintenance of information during working memory. *The Journal of Neuroscience*, *39*(19), 3728–3740. https://doi.org/10.1523/JNEUROSCI.2764-18.2019

Richard, A. M., Luck, S. J., & Hollingworth, A. (2008). Establishing object correspondence across eye movements: Flexible use of spatiotemporal and surface feature information. *Cognition*, *109*(1), 66–88. https://doi.org/10.1016/j.cognition.2008.07.004

Riggall, A. C., & Postle, B. R. (2012). The relationship between working memory storage and elevated activity as measured with functional magnetic resonance imaging. *The Journal of Neuroscience*, *32*(38), 12990–12998. https://doi.org/10.1523/JNEUROSCI.1892-12.2012

Rolls, E. T., & Wirth, S. (2018). Spatial representations in the primate hippocampus, and their functions in memory and navigation. *Progress in Neurobiology*, *171*, 90–113. https://doi.org/10.1016/j.pneurobio.2018.09.004

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*(2), 225–237. https://doi.org/10.3758/PBR.16.2.225

Saiki, J. (2016). Location-unbound color-shape binding representations in visual working memory. *Psychological Science*, *27*(2), 178–190. https://doi.org/10.1177/0956797615616797

Saiki, J. (2019). Robust color-shape binding representations for multiple objects in visual working memory. *Journal of Experimental Psychology: General*, *148*(5), 905–925. https://doi.org/10.1037/xge0000562

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntazy and automatic attentional control of visual working memory. *Perception & Psychophysics*, *64*(5), 754–763. https://doi.org/10.3758/BF03194742

Schneegans, S., & Bays, P. M. (2017). Neural architecture for feature binding in visual working memory. *The Journal of Neuroscience*, *37*(14), 3913–3925. https://doi.org/10.1523/JNEUROSCI.3493-16.2017

Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science*, *20*(2), 207–214. https://doi.org/10.1111/j.1467-9280.2009.02276.x

Shen, M., Tang, N., Wu, F., Shui, R., & Gao, Z. (2013). Robust object-based encoding in visual working memory. *Journal of Vision*, *13*(2), 1. https://doi.org/10.1167/13.2.1

Soto, D., & Humphreys, G. W. (2009). Automatic selection of irrelevant object features through working memory: Evidence for top-down attentional capture. *Experimental Psychology*, *56*(3), 165–172. https://doi.org/10.1027/1618-3169.56.3.165

Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(2), 248–261. https://doi.org/10.1037/0096-1523.31.2.248

van Moorselaar, D., Theeuwes, J., & Olivers, C. N. (2014). In competition for the attentional template: Can multiple items within visual working memory guide attention? *Journal of Experimental Psychology: Human Perception and Performance*, *40*(4), 1450–1464. https://doi.org/10.1037/a0036229

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*(6984), 748–751. https://doi.org/10.1038/nature02447

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 92–114. https://doi.org/10.1037/0096-1523.27.1.92

Wang, B., Cao, X., Theeuwes, J., Olivers, C. N., & Wang, Z. (2016). Location-based effects underlie feature conjunction benefits in visual working memory. *Journal of Vision*, *16*(11), 12. https://doi.org/10.1167/16.11.12

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48–64. https://doi.org/10.1037/0096-3445.131.1.48

Williams, L. G. (1967). The effects of target specification on objects fixated during visual search. *Acta Psychologica*, *27*, 355–360. https://doi.org/10.1016/0001-6918(67)90080-7

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238. https://doi.org/10.3758/BF03200774

Woodman, G. F., & Vogel, E. K. (2008). Selective storage and maintenance of an object's features in visual working memory. *Psychonomic Bulletin & Review*, *15*(1), 223–229. https://doi.org/10.3758/PBR.15.1.223

Xu, Y. (2002a). Encoding color and shape from different parts of an object in visual short-term memory. *Perception & Psychophysics*, *64*(8), 1260–1280. https://doi.org/10.3758/BF03194770

Xu, Y. (2002b). Limitations of object-based feature encoding in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(2), 458–468. https://doi.org/10.1037/0096-1523.28.2.458

Yin, J., Zhou, J., Xu, H., Liang, J., Gao, Z., & Shen, M. (2012). Does high memory load kick task-irrelevant information out of visual working memory? *Psychonomic Bulletin & Review*, *19*(2), 218–224. https://doi.org/10.3758/s13423-011-0201-y

Zelinsky, G. J. (1996). Using eye saccades to assess the selectivity of search movements. *Vision Research*, *36*(14), 2177–2187. https://doi.org/10.1016/0042-6989(95)00300-2

Zhang, B., Liu, S., Doro, M., & Galfano, G. (2018). Attentional guidance from multiple working memory representations: Evidence from eye movements. *Scientific Reports*, *8*, 13876. https://doi.org/10.1038/s41598-018-32144-4

Zhang, W., & Luck, S. J. (2009). Feature-based attention modulates feedforward visual processing. *Nature Neuroscience*, *12*(1), 24–25. https://doi.org/10.1038/nn.2223

Zhou, C., Lorist, M. M., & Mathôt, S. (2020). Concurrent guidance of attention by multiple working memory items: Behavioral and computational evidence. *Attention, Perception, & Psychophysics*, *82*(6), 2950–2962. https://doi.org/10.3758/s13414-020-02048-5

Received October 7, 2020
Revision received June 4, 2021
Accepted June 16, 2021 ■